Determining of Poisson's Ratio and Young's Modulus of Pumpkin Tissue: Using Laser Measurement Sensors

Maryam Shirmohammadi[1*], Prasad KDV Yarlagadda[2]
[1,*]University of South Australia, Adelaide, Australia; [2]Queensland University of Technology, Brisbane, Australia
[1]maryam.shirmohammadi@unisa.edu.au
[2]y.prasad@qut.edu.au

Abstract

Knowledge of the mechanical properties of food products is necessary to develop better designs and practices for agricultural operations and to reduce mechanical damage on tissue. A Universal Testing Machine was used to assess mechanical properties of peel, unpeeled and flesh samples of the Japanese variety of pumpkin (Cucurbita Maxima). Laser measurement sensors were used during the uniaxial compression test to capture the lateral displacement of unpeeled and flesh samples. Mechanical parameters—including elastic modulus, bio-yield point, Poisson's ratio and maximum lateral displacement—were measured and calculated. A different shape of curve was observed for the peel when compared with unpeeled and flesh samples due to the difference in the structure, moisture level and cellular arrangement of tissues. The values of stress and strain for flesh samples were lower than the calculated values for unpeeled samples. Poisson's ratio was determined for unpeeled and flesh tissues at 0.33 and 0.43, respectively. The ratio of stress over strain under linear limit was determined for flesh and unpeeled samples, which were close to the elastic modulus values for each sample. The elastic modulus found for the peel sample was relatively higher than unpeeled and flesh tissues.

Keywords: Elastic limit, axial loading, lateral displacement, elastic modulus, Poisson's ratio, compressive loading, laser measurement sensor, mechanical properties.

Introduction

Agricultural products undergo several mechanical stages from harvesting through to grading and packaging. Mechanical damage occurring during these stages can vary from small bruising to deep cuts, which is a direct loss when product is rejected in the sorting and grading phases [1, 2]. Damage to different parts of tissues such as skin, flesh or core might not be immediately visible but can cause physiological deterioration and a higher volume of loss over time [3]. A knowledge of mechanical properties of agricultural products provides the base line to design or optimise mechanised operations to a level where the lowest possible damage is created on the tissue.

The mechanical behaviours of food materials include a range of parameters under both elastic and plastic deformation ranges. There have been previous studies on determining these mechanical properties; however, some of these parameters are not easy to calculate. Due to the different structural arrangements of cells and the variable response to loading, [4] these parameters need to be carefully investigated under laboratory conditions. Poisson's ratio, the modulus of elasticity and the bio-yield point are some of these parameters. Poisson's ratio is "the negative of the ratio of transverse strain to corresponding axial strain resulting from an axial stress below the proportional limit of the material" [5]. Poisson's ratio has different values if the material is not isotropic. In other words, for anisotropic material the rate of displacement in each direction will be different. Both compression and tensile loading have been used to define the mechanical properties for food materials [5-11]. Poisson's ratio for food materials is considered between 0.25-0.5; for apple tissue it is stated to be between 0.25-0.35, and 0.49 for potato tissue [12]. The reported values for different varieties of onion were 0.15 and 0.44 [13], however, the method used to define Poisson's ratio affects the accuracy of values determined. Although the value of Poisson's ratio is highly affected by the percentage of moisture content, stress value and the loading speed [14], the structure of tissue and sampling method play an important role in determining this value. The load resistance level of peel differs from the flesh and softer part of tissue, which leads to different mechanical and physical responses. This paper's focus is on determining Poisson's ratio, elastic modulus and bio-yield point of pumpkin flesh, peel and unpeeled tissues under uniaxial compression [15 , 16, 17]. Laser measurement sensors were used to determine Poisson's ratio of pumpkin tissues. This work was part of an FEA modelling of the mechanical peeling of pumpkin.

Material and Methods

Samples of the Japanese variety of pumpkin were purchased from a local shop in Brisbane, Australia. The pumpkins selected for the tests were defect-free and ripe with no sign of skin damage or cuts on the surface. In this study, the material behaviour was assumed to be elastic and the effect of deformation rates on material behaviour was not considered as a factor. Moisture content was assumed as staying constant during the test, and all the sample preparation and testing was completed under laboratory conditions. During the sample preparation and prior to testing, samples were kept in sealed plastic bags to eliminate moisture loss.

Force versus deformation curves were obtained by performing compression tests on pumpkin samples. Considering the response of material to the loading to be elastic, the stress, strain and elastic modulus of food products are calculated using [12, 18]:

$$\sigma = \frac{F}{A}$$

$$\varepsilon = \frac{L_1 - L_0}{L} = \frac{\Delta L}{L} \qquad \text{Equation 1}$$

Where $\sigma, \varepsilon, F, A, L$ and ΔL are stress (Mpa), strain, force (N), area (mm^2), length (mm) and deformation (mm). Among the mechanical and physical properties of food materials, some of the parameters require a more specific and precise measurement. Poisson's ratio is one of these parameters where both lateral and axial displacements of samples need to be measured. There are different methods introduced to determine Poisson's ratio of food products [5, 7, 10, 11, 13]. For small specimens such as food particles, the elastic modulus of constrained and unconstrained axial loading can also be used to calculate Poisson's ratio [6]:

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L}$$

$$\nu = \frac{1}{4}\left(R + \sqrt{R^2 - 8R}\right) \qquad \text{Equation 2}$$

$$R = \frac{E_u}{E_c} - 1$$

In, Equation 2, E_u and E_c are Elastic Moduli in unconstrained and constrained uniaxial loading testing.

Determining the axial and lateral displacement of tissue is another method of calculating Poisson's ratio value [5]:

$$\nu = \frac{lateral\ strain}{axial\ strain} = \frac{\frac{\delta R}{R_0}}{\frac{\delta h}{h_0}} \qquad \text{Equation 3}$$

Additionally, Poisson's ratio can be calculated using: $\mu = \frac{E}{G}$ in an isotropic case and $\mu = \left(\frac{E}{2G}\right) - 1$ for anisotropic materials where E and G are Young's modulus and shear modulus, respectively [5].

When a compressive or tensile load is applied to a solid particle, deformation will happen in the direction of force, plus expansion or shrinkage in lateral directions depending on the direction of force. In this study, a uniaxial compression test [19] was performed on flesh, unpeeled and peel tissues of Japanese variety of pumpkin (Cucurbita maxima) [20, 21] at a speed of 20 mm/min. Axial displacement was recorded during the compressive loading by a Universal Testing Machine; for the lateral displacement a pair of laser measurement sensors (AR200) was used (Figure 1). Computer sensors have been used to measure the lateral displacement of food particles under uniaxial loading previously [14]. As shown in Figure 1, the lasers were installed on both sides of the sample under loading. These sensors observe the reflected light from the sides of the target surface. The sum of sensor recorded values provided the total expansion of the samples in a lateral direction.

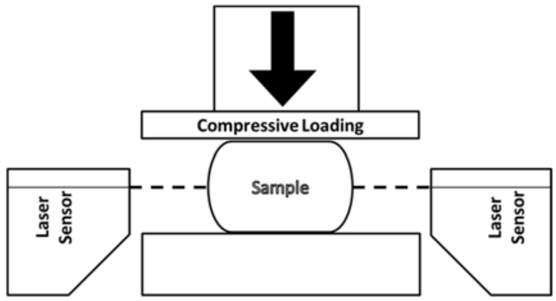


Figure 1: the experimental setup for recording axial and lateral displacement of samples under compression test.

The lasers both pointed at the same height on the samples, and recording lateral displacement was performed only for the flesh and unpeeled samples. Cylindrical samples were prepared with a diameter of 40 mm and an average height of 34.44 mm, 45.48 mm and 5 mm for flesh, unpeeled and peel samples, respectively. The moisture content was considered constant and all the samples were kept in plastic packs before the test to reduce the loss of moisture during testing. The results of the testing were then used to calculate the stress versus strain curve, elastic modulus and Poisson’s ratio of the samples. For peel samples, however, due to the low thickness (5 mm) it was not possible to record the lateral displacement. But the force versus deformation curve was obtained and stress–strain curve and elastic modulus were calculated.

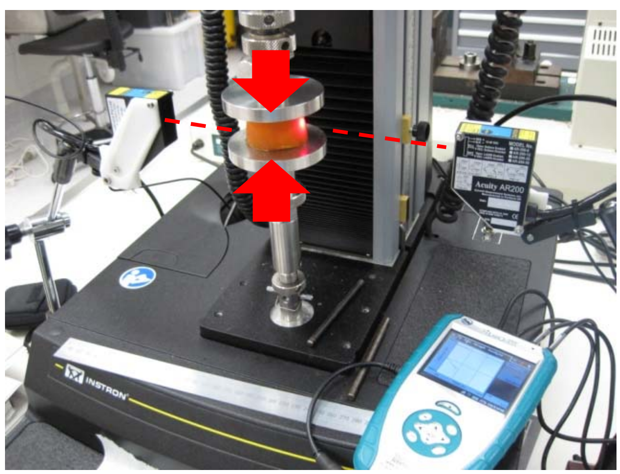


Figure 2: Compression test on cylindrical samples of pumpkin flesh using laser measurement sensors to record lateral displacement.

Elastic modulus and bio-yield point details were determined for the three samples. Elastic modulus was calculated as the ratio of stress over strain at the bio-yield point, and the slope of stress versus strain curve was also determined as the apparent elastic modulus [6, 22]. For the peel samples, due to the thickness of tissue and the experimental test safety procedures, the results of force versus deformation were only obtained to the point that maximum possible deformation reached. For all three samples, force versus deformation curves were plotted and a linear equation for the elastic zone was determined for unpeeled and flesh samples. For peel results, because of the downward concave shape of the curve, more than one equation was determined to capture the gradual change in curve slope.

Results and Discussion

Pumpkin flesh and peel tissue have different responses to mechanical loading including peeling, cutting, compression, impact and vibration [23]. Depending on the application and the type of mechanised process, the applied load can create different impacts on the tissue which are highly influenced by the tissue characteristics. The strength of the tissue and the cellular structure affects [4] the type and volume of damaged caused by loading. In analysing the mechanical behaviours of materials under different types of loading, the tendency of particles to expand or shrink in a perpendicular direction to loading is used to define Poisson's ratio. Regarding the difficulties associated with performing relevant experimentations to determine Poisson's ratio for different types and varieties of agricultural crops, this value is usually considered to be between 0.25-0.5 [7, 12]. In this study, uniaxial compression tests were performed on cylindrical samples with known dimensions; both axial and lateral displacements were recorded (Figure 2). The low thickness of peel samples limited the compression test results to a semi-linear section of curve and peak force and deformation value. Due to the low thickness, the rupture point was not achieved for peel samples (Figure 3 and Figure 4).

The linear limit (LL), bio-yield point (Y), and rupture point (R) were determined for each sample based on the force and deformation curve shape for agricultural materials [12] (see Figure 3 to Figure 5). The curves plotted for unpeeled and flesh samples followed a similar regime to yielding and rupture while the peel samples responded differently under the elastic limit.

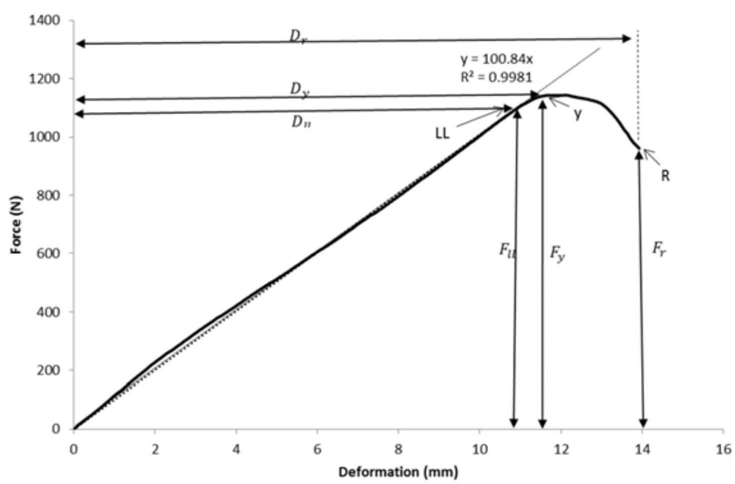


Figure 3: Force–deformation curve for pumpkin flesh samples under compressive loading.

The force versus deformation curve for peel samples did not follow a fully linear section to the peak for value as was observed for unpeeled and flesh samples [4 , 24, 25]. The curve obtained for peel was similar to what has previously been introduced as a compressible curve [26]. The concave shape of the curve showed the effects of yielding on the structure and the straining happening under loading [26].

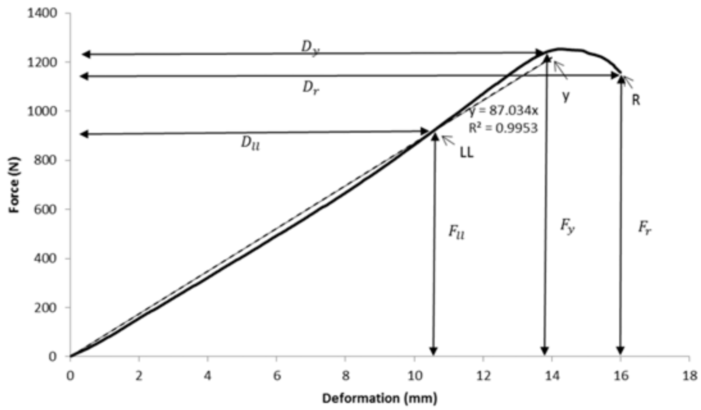
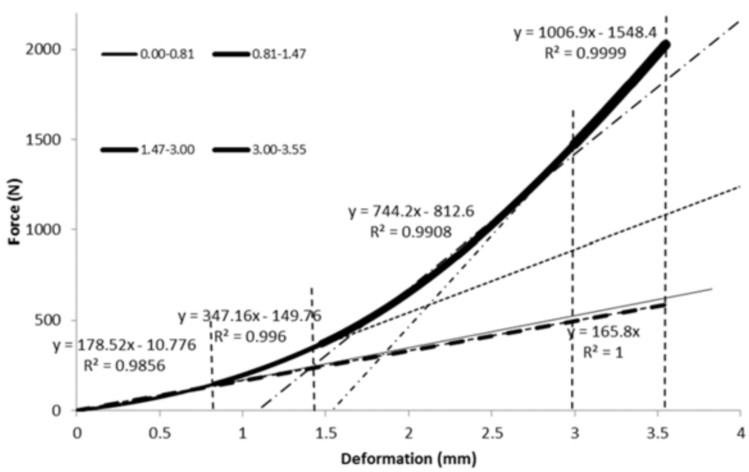
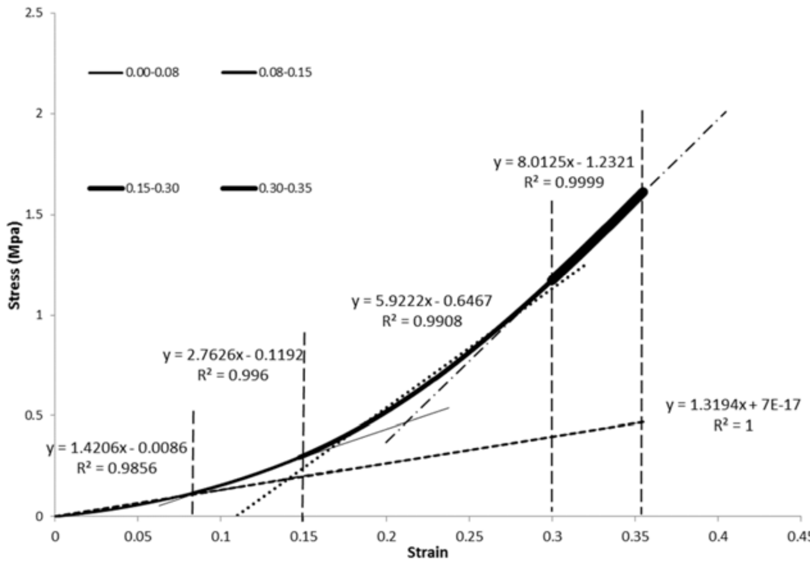


Figure 4: Force–deformation curve for pumpkin unpeeled samples under compressive loading.

Unpeeled samples underwent a larger deformation which led to rupture in comparison with the flesh samples. And, the maximum yielding forces for flesh samples were slightly lower than the unpeeled samples. The load values obtained for peel were higher than both unpeeled and flesh samples (Figure 5). The higher strength of the peel under mechanical loading can protect flesh tissue from damage and protect the product's textural quality of flesh during mechanised operations. The impact of peel in maintaining the fruit's firmness and quality during harvest and post-harvest operations has been studied before [27].



(a)



(b)

Figure 5: (a) Force–deformation curve and (b) stress–strain curve for pumpkin peel samples under compressive loading.

The concave downward shape of the force versus deformation curve obtained for peel samples has been reported previously for some fruits and vegetable [28]. The downward concave curve pattern has been observed for apples and potatoes [29], raisins [30], red lentils [31], and tomatoes [32] in literature. The stiffness value or the slope of the tangent line determined for different sections of force versus deformation curve for peel sample showed that under different deformation values, the force over deformation ratio varies from lower to higher. Table 1 shows the equations determined for force as the function of deformation and stress as the function of strain. For food materials, a rapid change in the rate of slope at the lower level of compressive loading has been reported previously [28]. The resistance of tissue to the stress due to moisture content has been observed for fruit and vegetables by researchers [32]. A high moisture content of 82%, 84% and 87% has been determined for pumpkin peel, unpeeled and flesh samples, respectively, [33] which affected the response of tissue to loading.

Table 1: Slope of force versus deformation curve for peel sample.

Deformation Range (mm)	Equation (force–deformation)	R^2	Equation (stress–strain)	R^2
0.00 to 0.83	F = 178.52d - 10.776	0.9856	$\sigma = 1.4206\varepsilon - 0.0086$	0.9856
0.83 to 1.47	F = 343.87d - 146.29	0.9962	$\sigma = 2.7626\ \varepsilon - 0.1192$	0.996
1.47 to 2.99	F = 740.36d - 802.86	0.9904	$\sigma = 5.9222\ \varepsilon - 0.6467$	0.9908
0.29 to 3.55	F = 1006.9d - 1548.4	0.9999	$\sigma = 8.0125\ \varepsilon - 1.2321$	0.9999
0.00 to 3.55	F = 460.36d	0.8571	$\sigma = 3.6789\ \varepsilon$	0.859
2% of max Deformation	F = 165.8d	1	$\sigma = 1.3194\ \varepsilon$	1

The average stress and strain for unpeeled samples were higher than the values for the flesh samples (Table 2). The equation for the tangent linear line for the elastic section of the curve showed a close trend to a fully linear relationship, unlike the results for peel samples. The R^2 values for flesh were on average 0.998 for flesh and 0.995 for unpeeled samples (**Error! Reference source not found.** and **Error! Reference source not found.**).

Poisson's ratio values for unpeeled and flesh samples were 0.33 and 0.43, respectively (Table 4). The maximum lateral deformation for unpeeled samples was lower than the value for flesh samples, which shows the effects of the combined structure of peel and flesh in unpeeled samples in comparison with flesh only. The lower value of Poisson's ratio in unpeeled samples can be related to the different moisture content levels of the two samples. Additionally, the structure of tissue—with bigger cells for flesh in comparison with smaller cell size and dense cellular structure of peel [4]—has affected the values obtained. Poisson’s ratio values estimated in this study were comparable with the values reported for the McIntosh apple (0.34), potato (0.49) [12] and apricot (0.40) [34], but higher than African nutmeg (0.30) [11]. The tissues with higher moisture content [28] have been reported with high value of Poisson’s ration, such as potato flesh (0.49), which is close to Poisson’s ratio of incompressible materials. The tissues with a high rate of cellular gas, such as some varieties of apple, however, have lower Poisson’s ratio values [35], for instance Red Delicious and Winesap varieties of apple with Poisson’s ratio of 0.21 and 0.29, respectively [12]. The reported values for cantaloupe melon were 0.338 and 0.334 for flesh and peel layers of fruit, respectively [36].

For peel samples, the maximum obtained force versus deformation curve was considered to be the bio-yield point. The elastic modulus was also determined, as the ratio of stress over strain at the bio-yield point was higher for the peel sample than the two other samples. The elastic modulus at the bio-yield point was similar for flesh and unpeeled samples, however, the average value for the elastic section of the curve and standard deviation shows that there was a higher difference between the elastic modulus values for unpeeled samples in comparison with flesh samples. The value was even higher for the peel samples, which was due to the reported curve shape and the concave pattern of force versus deformation obtained for the peel layer.

Table 2: Results of Elastic Modulus and Poisson’s Ratio for flesh and unpeeled samples.

	Stress–Strain curve	Poisson’s Ratio		Elastic Modulus (Mpa)		
		AV.	SD	Bio-Yield	AV.	SD
Flesh	Y=3.4x (R^2=0.008)	0.434	0.061	3.271	3.56	0.322
Unpeeled	Y=3.1x (R^2=0.995)	0.334	0.059	3.213	3.052	0.546
Peel	-	-	-	7.197	4.353	1.797

Sadrnia et al. [37] and Canet et al. [8] performed compression tests on cylindrical samples of watermelon and potato. The elastic modulus of peel was higher than unpeeled and flesh samples; this was similar to what has been reported for watermelon peel and flesh [37]. However, due to the difficulty of recording the lateral displacement, no values were reported for Poisson’s ratio of tough-skinned vegetables. The values obtained for flesh samples was 3.27 Mpa lower than the value reported previously for watermelon peel of Crimson sweet and Charleston gray varieties (4.9 and 5.36 Mpa) [37] and potato samples (4.8 Mpa) [8].

Conclusion and Future Work

A uniaxial compression test was performed on flesh, peel and unpeeled samples of Japanese variety of pumpkin. Both the axial and lateral displacements of flesh and unpeeled samples were recorded using a Universal Testing Machine and laser measurement sensors. The values of stress and strain, bio-yield point, elastic modulus, and Poisson’s ratio for the samples were calculated and presented. The results showed a difference in the force versus deformation curve of peel samples in comparison with the two other samples. The slope of the curve and equations for the linear limit (LL) of each curve was determined. A discussion developed on the differences between the samples’ response to the loading. The elastic modulus of peel samples was higher than flesh and unpeeled; in addition, the flesh sample had the lowest elastic modulus values. The maximum lateral displacement for flesh was higher than the unpeeled samples.

Due to the low thickness of the peel layer and the capability of the testing device to capture the lateral displacement and rupture point of peel samples, the following suggestions were made for future investigation. Determining the lateral displacement of peel tissue under tensile loading will give the possibility of recording lateral displacement. However, due to the tissue character and difficulty of performing tensile tests, using common methods applied on bio-tissues might also be applicable. Using grid lines to measure the deformation of thin-layer tissue has been used in biomedical research previously [38]. This method allows researchers to capture the displacement happening on the samples with smaller dimensions along different axes in microstructural levels. Recording the lateral displacement of a multilayer sample made of layers of peel under compressive loading can be another alternative method for future tests. To capture the effects of viscoelastic behaviour of tissue, further testing with different compressive loading is recommended.

References

1. DIOP, A., *Storage and processing of roots and tubers in the tropics*, ed. D.J.B. Calverley. 1998: FAO.
2. Varela, P., A. Salvador, and S. Fiszman, *Changes in apple tissue with storage time: rheological, textural and microstructural analyses.* Journal of Food Engineering, 2007. **78**(2): p. 622-629.
3. Rohm, H., D. JAROS, and M. DeHAAN, *A VIDEO‐BASED METHOD FOR DETERMINATION OF AVERAGE STRESS‐STRAIN RELATIONS IN UNIAXIAL COMPRESSION OF SELECTED FOODS.* Journal of texture studies, 1997. **28**(3): p. 245-255.
4. Shirmohammadi, M. and P.K.D.V. Yarlagadda, *Study of structural changes of pumpkin tissue before and after mechanical loading.* Applied Mechanics and Materials, 2013. **333-335**(2013): p. 1998-2003.
5. ASTM, *Standard Test Method for Poisson's Ratio at Room Temperature*. 2004.
6. *Texture in Food volume2: solid foods*, ed. D. Kilcast. Vol. 2. 2004, Cambridge: Woodhead Publishing Limited
7. Grotte, M., et al., *Young's modulus, Poisson's ratio, and Lame's coefficients of golden delicious apple.* International Journal of Food Properties, 2002. **5**(2): p. 333-349.
8. Canet, W., M.D. Alvarez, and M. Gil, *Fracture behaviour of potato samples (cv. Desiree) under uniaxial compression.* Journal of food engineering, 2007. **82**(4): p. 427-435.
9. Sitkei, G., *Mechanics of agricultural materials*. 1987, New York: Access Online via Elsevier.
10. Chappell, T.W. and D.D. Hamann, *Poisson Ratio and Young's Modulus for Apple Flesh under Compressive Loading.* ASAE, 1968: p. 608-610.
11. Burubai, W., et al., *Determination of Poisson's ratio and elastic modulus of African nutmeg (Monodora myristica).* International Agrophysics, 2008. **22**(2): p. 99.
12. Mohsenin, *Physical properties of plant and animal materials: structure, physical characteristics, and mechanical properties*. second ed. 1986, New York: Routledge. 891.
13. Cakir, E., F. Alayunt, and K. Özden, *A Study on the Determination of Poisson's Ratio and Modulus of Elasticity of Some Onion Varieties.* Asian Journal of Plant Sciences, 2002. **1**(4): p. 376-378.
14. Arana, I., *Physical properties of foods: novel measurement techniques and applications*. 2012: CRC Press.
15. Maryam Shirmohammadi, P.K.Y., *Deformation and stress distribution on pumpkin tissue during mechanical peeling using nonlinear Finite Element Modelling*
16. Shirmohammadi, M. and P.K.D.V. Yarlagadda, *Deformation and stress distribution in pumpkin during mechanical peeling using nonlinear Finite Element Modelling* Journal of Food Engineering, 2014.
17. Shirmohammadi, M., et al., *Mechanical Behaviours of Pumpkin Peel under Compression Test.* Journal of Advanced Materials Research, 2011. **337**: p. 3-9.
18. Sahin, S. and S.G. Sumnu, *Physical properties of foods*. 2006, Ankara: Springer.
19. Standards, A., *Compression Test of Food Materials of Convex Shape*. 2008. p. ASABE s368.4.
20. Whealy, K. and S. Ashworth, *Seed to Seed: Seed Saving and Growing Techniques for the Vegetable Gardener*. 2012: Chelsea Green Publishing.

21. Ferriol, M., B. Picó, and F. Nuez, *Morphological and molecular diversity of a collection of Cucurbita maxima landraces.* Journal of the American Society for Horticultural Science, 2004. **129**(1): p. 60-69.
22. Abbott, J.A., *Quality measurement of fruits and vegetables.* Postharvest Biology and Technology, 1999. **15**(3): p. 207-225.
23. Emadi, B., V. Kosse, and P.K.D.V. Yarlagadda, *Abrasive peeling of pumpkin.* Journal of Food Engineering, 2007. **79**(2): p. 647-656.
24. Shirmohammadi, M. and P.K.D.V. Yarlagadda, *Experimental Study on Mechanical Properties of Pumpkin Tissue.* Journal of Achievements in Materials and Manufacturing Engineering, 2012. **54**(1): p. 16-24.
25. Shirmohammadi, M. and P.K.D.V. Yarlagadda, *Properties of Tough Skinned Vegetable-Pumpkin Tissue*, in *11th Global Congress on Manufacturing and Management GCMM2012*. 2012, AUT University Auckland New Zealand: Auckland
26. Peleg, M., *The basics of solid foods rheology.* Food texture, 1987: p. 3-33.
27. Costa, F., *Mechanical investigation to assess the peel contribution in apple fruit.* Postharvest Biology and Technology, 2016. **111**: p. 41-47.
28. Bourne, M., *Food Texture and Viscosity- Concepts and Measurement*. 2002, New York: Academic Press.
29. Holt, J. and D. Schoorl, *Fracture in potatoes and apples.* Journal of Materials Science, 1983. **18**(7): p. 2017-2028.
30. Lewicki, P.P. and W.E. Spiess, *Rheological properties of raisins: Part I. Compression test.* Journal of food engineering, 1995. **24**(3): p. 321-338.
31. Ross, K., et al., *INTERPRETATION OF THE FORCE–DEFORMATION CURVES OF COOKED RED LENTILS (LENS CULINARIS).* Journal of Texture Studies, 2009. **40**(1): p. 109-126.
32. Babarinsa, F. and M. Ige, *Young's Modulus for Packaged Roma Tomatoes under Compressive Loading.* International Journal Of Scientific & Engineering Research. **3**(10): p. 314-320.
33. Shirmohammadi, M., *Process Modelling and Simulation of Tissue Damage during Mechanical Peeling of Pumpkin as Tough Skinned Vegetable*. 2013, Queensland University of Technology: Brisbane. p. 301.
34. Erdoğan, D., et al., *Mechanical harvesting of apricots.* Biosystems engineering, 2003. **85**(1): p. 19-28.
35. Steffe, J., *Rheological methods in food process engineering*. 1996: Freeman Press.
36. Seyedabadi, E., M. Khojastehpour, and H. Sadrnia, *Predicting Cantaloupe Bruising Using Nonlinear Finite Element Method.* International Journal of Food Properties, 2014(just-accepted).
37. Sadrnia, H., et al., *Internal bruising prediction in watermelon compression using nonlinear models.* Journal of Food Engineering, 2008. **86**(2): p. 272-280.
38. Thorpe, C., et al., *TENDON FASCICLES SHOW AN AGE-SPECIFIC RESPONSE TO CYCLIC FATIGUE LOADING.* Bone & Joint Journal Orthopaedic Proceedings Supplement, 2014. **96**(SUPP 11): p. 162-162.